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TITLE: PROJECTED PERFORMANCE OF RF-LINAC-DRIVEN FREE-ELECTRON LASERS IN THE EXTREME-ULTRAVIOLET SPECTRAL REGION

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Projected Performance of RF-Linac-Driven Free-Electron Lasers in the Extreme-Ultraviolet Spectral Region.*

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Abstract

A free-electron laser user facility for scientific experimentation in the vacuum-ultraviolet and soft x-ray spectral regions (together termed the XUV) is being developed at Los Alamos. The design includes a series of laser oscillators and amplifiers, driven by a single, rf-linear accelerator, that will generate broadly tunable, picosecond-pulse, coherent radiation from 1 to 400 nm. Below 300 nm, the peak- and average-power output of these FEL devices should surpass the capabilities of any existing, continuously tunable photon sources by many orders of magnitude. The design and output parameters of this facility will be described, including comparison with synchrotron radiation sources, and recent progress in developing the three primary components (electron beam, magnetic undulator, and resonator mirrors) will be reviewed.

Introduction

For the past four years, a multidisciplinary team of Los Alamos scientists, supported by the U.S. Department of Energy, has been developing the requisite technologies to extend free-electron laser (FEL) operation from infrared and visible wavelengths into the extreme-ultraviolet (XUV) below 100 nm using rf-linear accelerator technology. The goal is to establish an XUV Free-Electron Laser User Facility, the next-generation light source that will make available to researchers optical power more than one-million times greater than provided by synchrotron light sources. Based primarily on a series of FEL oscillators driven by a single, rf-linac, the Los Alamos facility is designed to generate broadly tunable, picosecond-pulse, coherent radiation spanning the soft x-ray through the ultraviolet spectral ranges from 1 nm to 400 nm.

With recent improvements, rf-linear accelerators now appear to be a viable alternative to storage rings as sources of the very bright electron beams (high peak current, low transverse emittance and energy spread) needed to enable FELs to operate in the XUV.[1] (Reference 2 reviews the various methods of generating FEL radiation below 100 nm.) RF linac FELs offer several potential advantages which include 1) the electrons pass through the FEL only once at 10^7 to 10^8 Hz without the constraints imposed by storing a recirculating beam including peak current dens

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ity limitation by the Touschek effect, 2) linac FELs can produce both high-peak and high-average output power simultaneously, 3) the linear geometry allows unrestricted and variable undulator length, 4) a number of FEL oscillators can be driven in series restricted only by the available laboratory space, and 5) the electrons exiting the FELs can be used to generate neutrons, positrons, and gamma rays for additional experiments in synchronism, if desired, with the FEL photons.

Los Alamos has been operating an infrared rf-linac-driven FEL between 9 and 45 µm since 1983. Recently, the Los Alamos linac has delivered peak currents ≥500 A, resulting in large values of optical gain (up to 400%/pass) at 10-µm from a short, 1-m undulator. Experience with this system has provided invaluable data with which to design a linac-based FEL light source as a scientific research facility in the extreme ultraviolet.[3-9] Over the last four years these efforts have resulted in the 3-D numerical code FELEX that correctly simulates emittance-dominated FEL physics in the XUV,[10] experimental development of a new high-brightness photocathode injector,[11] invention and implementation of an on-line method to monitor and correct magnetic-field errors in long undulators,[12,13] and laboratory demonstration of a new class of multifaceted, resonator mirrors for the XUV with retroreflectance ≥40% for wavelengths down to 35 nm (89% at 58 nm).[14-16]

XUV FEL Facility Design

FEL Oscillator Chain

The conceptual design of the proposed Los Alamos XUV FEL Facility is shown in Fig. 1, and design specifics are given in Table 1. It includes a series of FEL oscillators, driven by a single rf-linac, that should simultaneously span the soft x-ray through the ultraviolet spectral ranges from 1 nm to 400 nm. The shortest-wavelength oscillators are ordered first in the sequence since they require the highest-quality electron beam; the gain at longer wavelengths is less affected by beam degradation. Even so, all of the oscillators are designed to perturb the electron beam energy only very slightly, with the energy-extraction efficiency being less than 0.1%. Further beam degradation by wakefield effects in the beamline and magnetic undulator must be prevented by minimizing discontinuities. The number of oscillators may be increased arbitrarily, consistent with the amount of accumulated energy spread and/or emittance degradation in the electron beam. The operating wavelengths of each of the FELs will either be tuned as a group by varying the electron energy or independently over a smaller range by adjusting the undulator gaps.

FEL Amplifiers Based on Self-Amplified Spontaneous Emission

The feasibility of and output power from FEL oscillators will depend on the availability of resonator mirrors with sufficiently high reflectance to match the attainable small-signal gain. Satisfactory broadband mirrors have yet to be produced below 35 nm, and this spectral region may well become the domain of either coherent harmonic radiation generated within FEL oscillators or higher-power, single-pass FEL amplifiers based on self-amplified spontaneous emission (SASE). As indicated in Fig. 1, the proposed Los Alamos XUV FEL Facility will include a long SASE amplifier for wavelengths below 10 nm. SASE amplifiers are attractive since the problems of thermal distortion, laser damage, and cost of resonator mirrors are avoided.

To achieve single-pass optical gain of ~1000, which is only possible in the exponential-gain regime, much brighter electron beams and longer undulators will be required than for FEL oscillators. For example, 3-D numerical calculations by Goldstein, et al.,[17] predict that generation of ~12 MW peak power at 6 nm will require a 900-MeV electron beam with 200-A peak current, energy spread ≤0.1 %, and energy-normalized emittance (90% of electrons) of 4π mm-mr even with an ideal 30-m undulator amplifier with 1500 periods. These beam emittance and undulator requirements are especially demanding! At longer wavelengths from 20 to 40 nm, the requirements for amplifier operation are less stringent, but still demanding. At 20 nm, for example, 500 kW peak SASE power might be generated from a 16-m undulator with 1000 periods and a beam emittance twice as large (8π mm-mr) as needed for 6 nm.[9] If brighter electron beams do become achievable with the photocathode injector, even higher powers will produced.

Regenerative FEL Amplifiers

An intermediate variant between an FEL oscillator and an FEL amplifier based on SASE is a regenerative amplifier which uses two or more passes through the undulator to reach the final beam intensity. This scheme, suggested by both Goldstein et al.[17] and Kim,[18] requires end mirrors separated by half the arrival time of the electrons, as in an oscillator, but the mirror reflectance may be low, such as 10%. The required undulator length would be intermediate between that needed for an oscillator and a single-pass SASE amplifier. The process begins with SASE radiation generated from the first bunch of electrons. If the mirror reflectance returns more radiation to the undulator entrance than is generated by spontaneous emission from the next electron bunch of the pulse train, then the returned optical beam will experience more gain and will grow to a much higher level than by SASE alone. This method may be the most effective way of generating FEL radiation below 10 nm since a less demanding tradeoff can be made between the electron beam quality and the undulator length than is possible with a single-pass amplifier.

Predicted XUV FEL Output

We have performed 3-D numerical simulations using the FEL code FELEX[10] and its derivatives to predict the single-pass and multiple-pass gain in an XUV FEL resonator, the spectral bandwidth, and output power versus wavelength. Table 2 provides an abbreviated summary.

Since FELs appear to be the natural finale in the progression of light sources based on radiation from relativistic electrons passing through magnetic undulators, it is appropriate to compare their output performance with synchrotron radiation sources such as storage rings with wiggler and undulator insertion devices. A comparison of the predicted flux (photons/s/0.1% bandwidth) delivered to a sample target is presented versus wavelength in Fig. 2.

Development Schedule for an XUV FEL Facility

Prior to building a complete user facility, the Los Alamos FEL team proposes to conduct a series of FEL oscillator demonstrations at progressively shorter wavelengths, the first of which will be from 50 to 100 nm. By mid-1989, the status of the electron-beam, undulator, and mirror technologies should well support this experiment. The second-phase objective will be FEL oscillation in the 10- to 14-nm region, corresponding to the high-reflectance band of a Rh multifaceted mirror. This will require higher electron beam energy (additional accelerator structure) and a low-emittance electron beam possible only with a photocathode injector. Since the reflectance of mirrors below 10 nm is not high enough for laser oscillators, the third phase will produce coherent, 1- to 10-nm radiation by SASE within very long amplifier undulators. Successful completion of these three stages, will enable the multi-FEL facility to cover the entire 1- to 400-nm range with projected output radiation characteristics that were given in Table 2.

Free-Electron Laser Applications in the XUV

Numerous potential applications await the development and commissioning of a free-electron laser user facility operating in the extreme ultraviolet. As described by experts in various disciplines, the availability of several orders-of-magnitude more monochromatic photons per unit time (compared with of synchrotron radiation sources) in trains of picosecond pulses will significantly impact atomic and molecular science, photochemistry, biology, physics of materials, interfaces and surfaces, and detectors and optics.

The high-intensities can be used to induce nonlinear physical phenomena, diagnose short-lived phenomena in low-density targets, and outshine keV plasmas in terms of spectral brightness. The greater number of photons per second will increase the signal-to-noise-ratio of experiments that heretofore could not be conducted or will provide snapshots of temporally unstable targets. For details of particular applications that are anticipated for XUV FELs, the interested reader should consult the proceedings of the 1984 Castelgandolfo Workshop[22] and the OSA Topical Conference on *Free-Electron Laser Applications in the Ultraviolet* held at Cloudcroft, New Mexico on March 2-5, 1988.[23]

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Table 1. Design Parameters for RF-Linac FELs for the Ultraviolet to the Soft X-Ray Region

Electron beam	
Energy:	100 to 500 MeV, FEL oscillators 750 MeV to 1 GeV, FEL SASE amplifier
Peak current:	100 to 400 A, as required
Normalized emittance: (90% of electrons)	25π to 40π mm-mr, for oscillators $\leq 4\pi$ mm-mr, for a 16 m SASE amplifier
Energy spread:	0.1% to 0.2%, FWHM
Undulators	
Length:	8 m: 50-nm oscillator, 12 m: 10-nm oscillator
Period:	1.6 cm
Peak Axial Field:	7.5 kG
Resonator mirrors	
End mirrors:	R $\geq$40%, multifaceted flats + paraboloids with metal coatings: Al, Si, Ag, and Rh; also, CVD SiC for $\geq$60 nm
Beam-expanding hyperboloids:	Au coating on SiC or Si

Table 2. Projected Output Properties of the Proposed Los Alamos RF-Linac-Driven UV/XUV FEL Facility

Micropulse duration:	10 - 30 ps (FWHM); possibly compressible to < 1 ps
Micropulse repetition rate:	10^7 - 10^8 Hz
Macropulse duration:	300-µs, Rep. @ 30 Hz
Facility wavelength span :	1 nm to 400 nm, oscillators and SASE amplifiers
Spectral bandwidth:	1 cm^{-1} Fourier-transform limit of 10-ps pulse, up to ~1% if sidebands are allowed
Peak power at target:	>20 MW, for 200 to 400 nm, (1 cm^{-1} BW) 1 to ≥10 MW, for 12 to 100 nm, (1 cm^{-1} BW) 10 W, at 4 nm (3rd harmonic of 12 nm) 12 MW, at 6 nm (SASE amplifier)
Average power at target:	1 to >10 W for oscillators
Photon flux at target:	10^8 - 10^{15} photons/10-ps pulse, 1 - 400 nm, resp. 10^{15} - 10^{20} photons/sec, average, " " "
Spectral brightness:	≥10^{26}photons/sec/(mm-mr)^2/1cm^{-1} BW, peak ≥10^{20} photons/sec/(mm-mr)^2/1-cm^{-1} BW, aver.
Polarization:	Linear with circular/elliptical option
Temporal coherence:	Limited by Fourier transform of micropulses
Spatial coherence:	Near diffraction-limited focusability

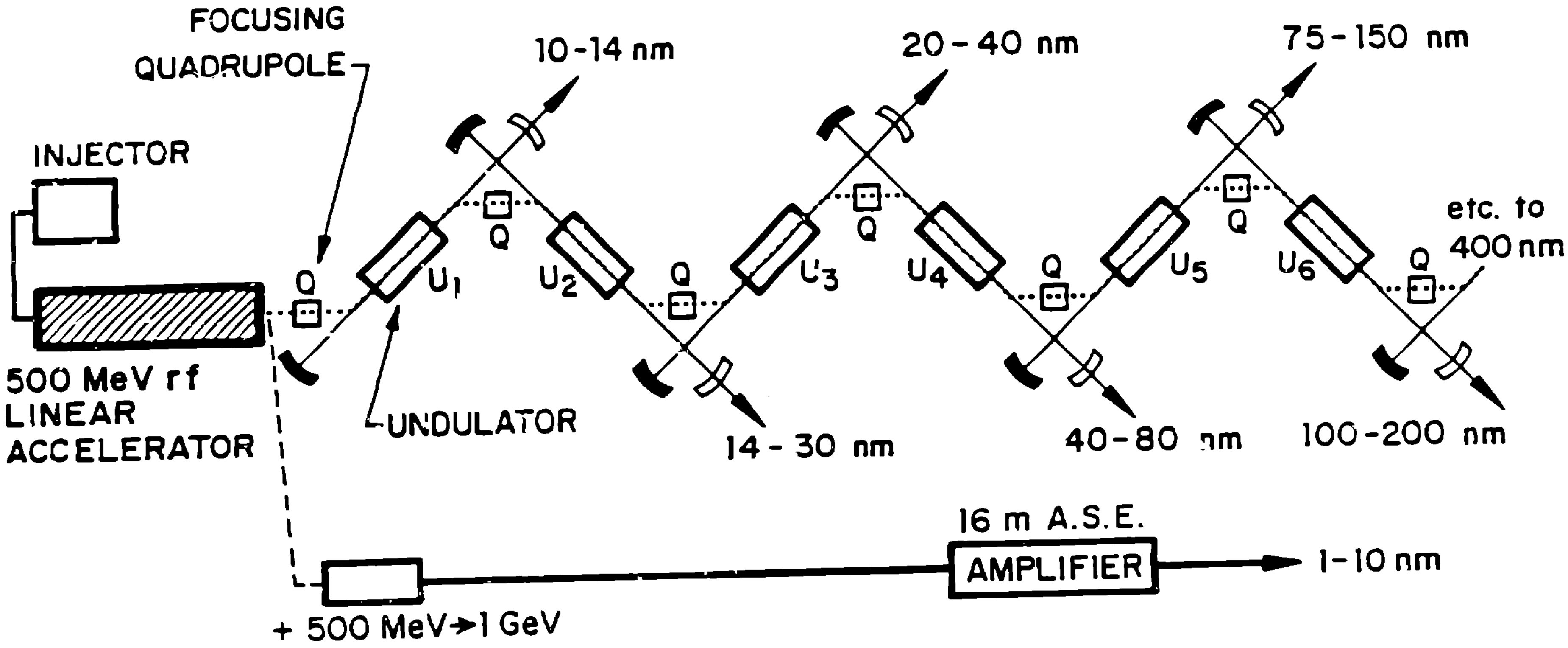
Figures

Figure 1. Configuration of the proposed Los Alamos XUV/UV FEL facility (1 to 400 nm). One rf-linear accelerator drives multiple, FEL oscillators in series. An additional long undulator will be used to produce 1- to 10-nm coherent pulses by SASE or in a regenerative (2- or 3-pass) amplifier using available mirrors.

Figure 2. The time-average spectral flux delivered on target by rf-linac FELs is compared with that predicted for the most powerful synchrotron light source designs represented by undulators in the LBL Advanced Light Source.[19-21] The FEL curves were calculated for the Los Alamos rf-linac FEL design, and a monochromator efficiency of 10% was applied to the published output curves for the synchrotron insertion devices. Besides narrower spectral bandwidth of ~1 cm^{-1}, the FEL has an additional factor of 3000 advantage in comparisons of <u>peak</u> spectral flux. To convert the time-average curves to peak values, the appropriate multiplier for the FEL is 10^6 (10 ps pulse every 100 ns during a 300-μs macropulse repeated at 30 Hz) and that for the storage-ring insertion devices is ~300.

CONFIGURATION OF THE PROPOSED LOS ALAMOS XUV/UV FREE-ELECTRON LASER FACILITY (1 to 400 nm)

ONE rf LINEAR ACCELERATOR DRIVES MULTIPLE, FEL OSCILLATORS IN SERIES



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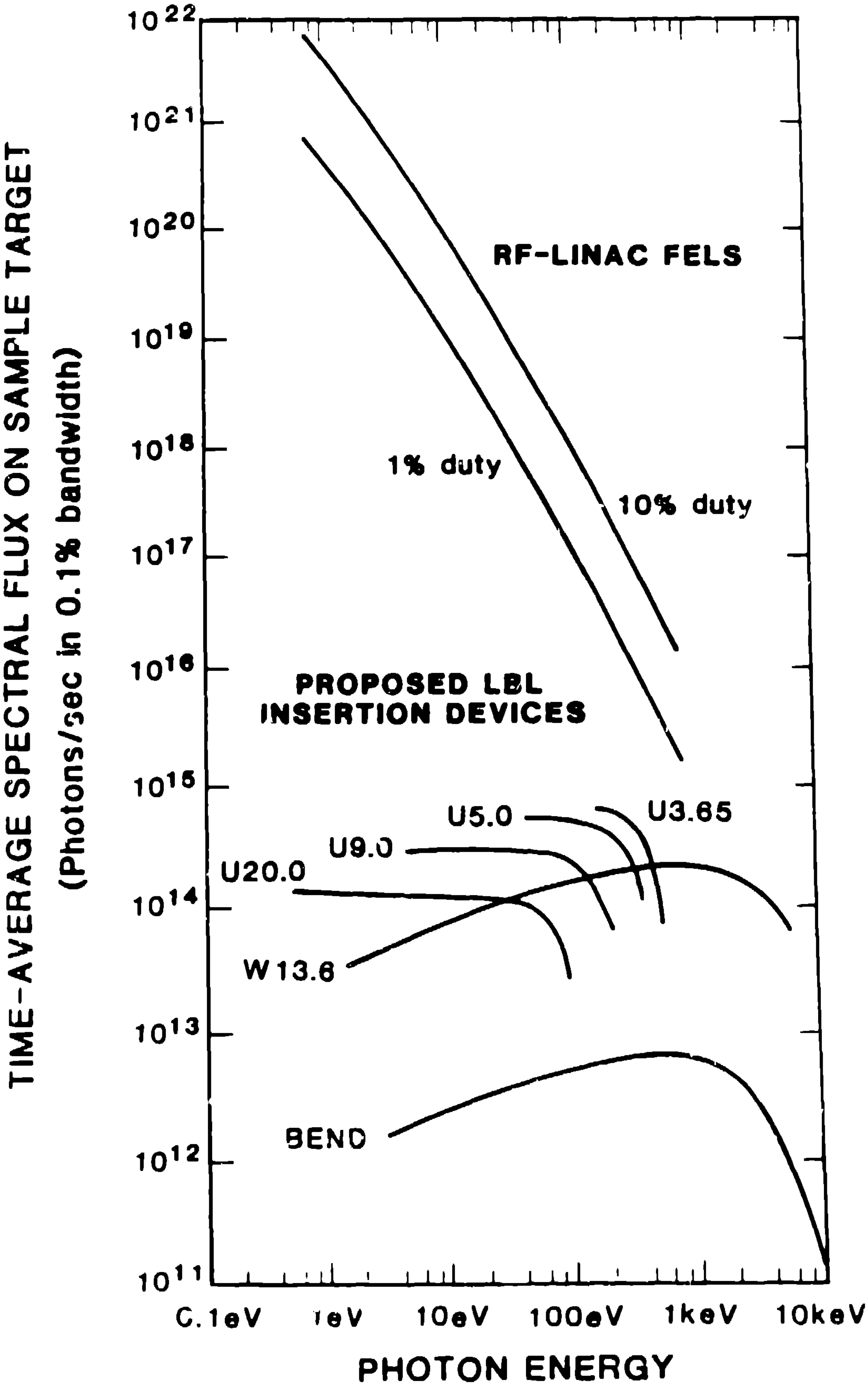

TIME-AVERAGE SPECTRAL FLUX ON SAMPLE TARGET
(Photons/sec in 0.1% bandwidth)
10 22
10 21
10 20
10 19
10 18
10 17
10 16
10 15
10 14
10 13
10 12
10 11
RF-LINAC FELS
1% duty
10% duty
PROPOSED LBL
INSERTION DEVICES
U5.0
U3.65
U9.0
U20.0
W13.6
BEND
C.1eV
1eV
10eV
100eV
1keV
10keV
PHOTON ENERGY